

## 1 PROJECTION EXPOSURE APPARATUS AND METHOD

BACKGROUND OF THE INVENTIONField of the Invention

5 The present invention relates to a projection exposure apparatus and method and, more particularly, to a scan type projection exposure apparatus and method used to manufacture semiconductor integrated circuits and liquid crystal devices.

10 Related Background Art

Many conventional apparatuses of this type have correction functions for imaging characteristics because the apparatuses need to maintain high imaging characteristics. Factors which cause the imaging characteristics to vary are changes in external environment such as atmospheric pressure and temperature, and slight absorption of exposure light by a projection optical system. With regard to changes in environment, the atmospheric pressure and the like are monitored by sensors, and correction is performed in accordance with the detection values, as disclosed in, e.g., USP 4,687,322. With regard to absorption of exposure light, light energy incident on a projection optical system is measured, and a change in imaging characteristic owing to absorption of exposure light is calculated on the basis of the measurement value, thereby performing correction, as disclosed in, e.g.,

15

20

25

1     USP 4,666,273. In this known method, light energy  
incident on the projection optical system through a  
mask is detected by, e.g., a photoelectric sensor  
arranged on a substrate stage. In addition to light  
5     energy for projection exposure, which is incident from  
the mask side, light energy is incident on the  
projection optical system after it is reflected by a  
photosensitive substrate. This light energy also  
changes the imaging characteristics of the projection  
10    optical system depending on the intensity. With regard  
to such light energy, for example, as disclosed in USP  
4,780,747, light reflected by a photosensitive  
substrate is measured by a photoelectric sensor  
arranged in an illumination optical system. The sensor  
15    receives the light through a projection optical system  
and a mask, and a total change in imaging  
characteristic is calculated in consideration of a  
change in imaging characteristic owing to this  
reflected light energy. In this method, light  
20    reflected by an optical member, a mask pattern, and the  
like is incident on the photoelectric sensor in the  
illumination optical system together with light  
reflected by the substrate. For this reason, a  
plurality of reference reflecting surfaces having  
25    different known reflectances are set on a substrate  
stage, and the ratio of the respective outputs from the  
photoelectric sensor, which correspond to the reference

1 reflecting surfaces, is obtained in advance. The  
reflectance (more accurately, reflection intensity) of  
the photosensitive substrate is obtained on the basis  
of this ratio. As described above, since light  
5 reflected by a mask pattern is superposed on light  
reflected by a photosensitive substrate, sensor outputs  
corresponding to a plurality of reference reflecting  
surfaces must be obtained every time a mask is  
replaced. Alternatively, sensor outputs must be  
10 measured and registered in advance.

Conventionally, the amount of change in imaging  
characteristic owing to absorption of exposure light is  
obtained to perform correction by the above-described  
methods.

15 The above conventional scheme has been developed  
on the basis of a scheme of projecting/exposing the  
entire mask pattern on a photosensitive substrate  
(called a batch exposure scheme or a full field  
scheme). Recently, however, a so-called scan exposure  
20 scheme has been developed, in which exposure is  
performed by illuminating a portion of a pattern area  
on a mask with a slit-like beam while moving the mask  
and a photosensitive substrate relative to each other.  
In this scheme, since the illumination area on a mask  
25 is smaller than that in the batch exposure scheme, the  
amount of image distortion or illuminance irregularity  
is small. Furthermore, no limitations are imposed on

1 the field size of a projection optical system in the  
scan direction, and hence large-area exposure can be  
performed.

5 In a scan type exposure apparatus, however, energy  
incident on the projection optical system changes while  
a mask is scanned with respect to a slit-like  
illumination beam. For example, such a change occurs  
because the area of a light-shielding portion (a  
chromium layer of a pattern) formed on a mask changes  
10 in accordance with the position of a slit illumination  
area on the mask, and hence the amount of energy  
incident on the projection optical system during a scan  
exposure operation changes.

15 In addition, the amount of light reflected by a  
mask pattern changes in accordance with the position of  
a mask. Therefore, the detection precision with  
respect to the amount of energy which is reflected by a  
photosensitive substrate and incident on the projection  
optical system inevitably deteriorates in the  
20 conventional scheme.

For the above-described reasons, in the  
conventional scheme, correction based on an accurate  
amount of change in imaging characteristic owing to  
absorption of exposure light cannot be performed.

25 SUMMARY OF THE INVENTION

It is an object of the present invention to  
provide a projection exposure apparatus of a scan

1 exposure scheme, which can properly correct the imaging characteristics.

In order to achieve the above object, according to a first aspect of the present invention, there is  
5 provided a projection exposure apparatus having an illumination optical system for illuminating a mask, on which a predetermined pattern is formed, with light from a light source, a projection optical system for forming an image of the pattern of the mask on a  
10 photosensitive substrate, a mask stage for holding the mask and moving the mask within a plane perpendicular to an optical axis of the projection optical system, a substrate stage for moving the photosensitive substrate within a plane conjugate to the plane with respect to  
15 the projection optical system, and imaging characteristic correction means for correcting an imaging characteristic of the projection optical system, the apparatus synchronously moving the mask and the photosensitive substrate along an optical axis of  
20 the projection optical system so as to expose an entire pattern surface of the mask, and the apparatus including:

incident light intensity input means for inputting an intensity of the illumination light, which is  
25 incident on the projection optical system through the mask, in accordance with a position of the mask;

1       imaging characteristic calculation means for  
calculating a variation in imaging characteristic of  
the projection optical system on the basis of  
information from the incident light intensity input  
5 means; and

control means for controlling the imaging  
characteristic correction means on the basis of a  
result obtained by the imaging characteristic  
calculation means.

10       According to a second aspect of the present  
invention, there is provided a projection exposure  
apparatus having an illumination optical system for  
illuminating a mask, on which a predetermined pattern  
is formed, with light from a light source, a projection  
15 optical system for forming an image of the pattern of  
the mask on a photosensitive substrate, a mask stage  
for holding the mask and moving the mask within a plane  
perpendicular to an optical axis of the projection  
optical system, a substrate stage for moving the  
20 photosensitive substrate within a plane conjugate to  
the plane with respect to the projection optical  
system, and imaging characteristic correction means for  
correcting an imaging characteristic of the projection  
optical system, the apparatus synchronously moving the  
25 mask and the photosensitive substrate along an optical  
axis of the projection optical system so as to expose

1 an entire pattern surface of the mask, and the  
apparatus including:

incident light intensity input means for inputting  
an intensity of the illumination light, which is  
5 incident on the projection optical system through the  
mask, in accordance with a position of the mask;

reflected light intensity input means for  
inputting an intensity of the illumination light, which  
is reflected by the photosensitive substrate and  
10 incident on the projection optical system again, in  
accordance with a position of the mask;

imaging characteristic calculation means for  
calculating a variation in imaging characteristic of  
the projection optical system on the basis of  
15 information from the incident light intensity input  
means and information from the reflected light  
intensity input means; and

control means for controlling the imaging  
characteristic correction means on the basis of a  
20 result obtained by the imaging characteristic  
calculation means.

According to the present invention, even if energy  
incident on the projection optical system changes when  
a mask is scanned during an exposure operation, no  
25 problem is posed because illumination light intensity  
data corresponding to the position of the mask can be  
used for calculation of a variation in imaging

1 characteristic caused by absorption of exposure light.  
In addition, according to the present invention, a  
variation in imaging characteristic owing to absorption  
of exposure light can be accurately obtained because  
5 energy incident on the projection optical system is  
calculated in consideration of information about light  
reflected by the photosensitive substrate.

As described above, according to the present  
invention, since a variation in imaging characteristic  
10 can be accurately calculated on the basis of the amount  
of energy incident on the projection optical system  
which changes in accordance with the position of a  
mask, the imaging characteristic can be corrected  
without any error even in a scan type exposure  
15 apparatus.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic block diagram showing the  
arrangement of a scan type exposure apparatus according  
to an embodiment of the present invention;

20 Fig. 2 is a perspective view showing a  
scan/exposure operation in the apparatus in Fig. 1;

Fig. 3 is a block diagram showing the detailed  
arrangement of components around the wafer stage of the  
apparatus in Fig. 1;

25 Fig. 4A is a graph showing incident energy;

1           Fig. 4B is a graph showing the relationship  
between the incident energy and the variation in  
magnification;

          Fig. 5 is a graph showing a change in reticle  
5   transmittance in a case wherein the reticle is moved;

          Fig. 6 is a graph showing the relationship between  
the reflectance and the reference reflectances;

          Fig. 7A is a graph showing the relationship  
between the reflectance and the reference reflectances  
10   in a case wherein the reticle is moved;

          Fig. 7B is a graph showing a change in reticle  
reflectance in a case wherein the reticle is moved;

          Fig. 8A is a graph showing the incident energy  
corresponding to each reticle position in a case  
15   wherein the reticle is scanned;

          Fig. 8B is a graph showing variations in incident  
energy and imaging characteristic in a case wherein the  
incident energy changes at the respective positions  
(timings);

20          Fig. 9 is a plan view showing the relationship  
between a reticle blind viewed from above and a  
projection field;

          Fig. 10 is a perspective view stereoscopically  
showing the illuminance distribution of illumination  
25   light; and

          Fig. 11 is a graph showing the illuminance  
distribution in the scan direction.

1    DESCRIPTION OF THE PREFERRED EMBODIMENTS

          An embodiment of the present invention will be described below with reference to the accompanying drawings. Fig. 1 is a schematic representation of the arrangement of a projection exposure apparatus suitable for an embodiment of the present invention.

          Illumination light IL emitted from a light source 1 passes through a shutter 2 and is adjusted to a predetermined beam diameter by a lens system 4 constituted by a collimator lens and the like. The illumination light IL is then incident on a fly-eye lens 6 through a mirror 5. The illumination light IL is an excimer laser beam such as a KrF or ArF laser beam, a harmonic wave of a copper vapor laser or a YAG laser, or an ultraviolet line from a super-high pressure mercury lamp. The shutter 2 is inserted/removed in/from an optical path by a shutter driver 3 to control opening/closing of the optical path. If the light source 1 is a pulse light source such as an excimer laser, the shutter 2 need not be used for light amount control.

          The light beam emerging from the fly-eye lens 6 is incident on a reticle (mask) R, on which a semiconductor circuit pattern or the like is drawn, through relay lenses 7a and 7b, a reticle blind 8, a mirror 9, and a condenser lens 10. The system constituted by the fly-eye lens 6, the relay lenses 7a

1 and 7b, the mirror 9, and the condenser lens 10 serves  
to superpose the illumination light IL emerging from  
the respective lens elements of the fly-eye lens 6 on  
the reticle R to illuminate the reticle R with a  
5 uniform light intensity. The light-shielding surface  
of the reticle blind 8 is conjugate to the pattern area  
of the reticle R. The size (slit width or the like) of  
the opening portion of the reticle blind 8 is adjusted  
by opening/closing a plurality of movable  
10 light-shielding portions (e.g., two L-shaped movable  
light-shielding portions) constituting the reticle  
blind 8 by using a motor 11. By adjusting the size of  
this opening portion, an illumination area IA for  
illuminating the reticle R is arbitrarily set. The  
15 reticle R is vacuum-chucked on a reticle stage RST  
disposed on a base 12. The reticle stage RST can be  
finely moved on the base 12 two-dimensionally through  
an air bearing and the like to position the reticle R  
within a plane perpendicular to an optical axis IX of  
20 the illumination system. The reticle stage RST can  
also be moved on the base 12 in a predetermined  
direction (scan direction) by a reticle driver 13  
constituted by a linear motor and the like. The  
reticle stage RST has at least a moving stroke which  
25 allows the entire surface of the reticle R to cross the  
optical axis IX of the illumination system. A movable  
mirror 15 for reflecting a laser beam from an

interferometer 14 is fixed to an end portion of the reticle stage RST. The position of the reticle stage RST in the scan direction is always detected by the interferometer 14 with a resolving power of about 0.01  $\mu\text{m}$ . Position information about the reticle stage RST, which is obtained by the interferometer 14, is supplied to a control system 16. The control system 16 controls the reticle driver 13 to move the reticle stage RST on the basis of the position information about the reticle stage RST. The initial position of the reticle stage RST is determined such that the reticle R is positioned to a reference position with high precision by a reticle alignment system. Therefore, the position of the reticle R can be measured with sufficiently high precision by only measuring the position of the movable mirror 15 using the interferometer 14.

The illumination light IL passing through the reticle R is incident on, e.g., a double side telecentric projection optical system PL. The projection optical system PL then forms a projection image, obtained by reducing the circuit pattern of the reticle R to 1/5 or 1/4, on a wafer W having a resist (photosensitive agent) coated on its surface.

In the exposure apparatus of this embodiment, as shown in Fig. 2, the reticle R is illuminated with the rectangular (slit-like) illumination area IA whose longitudinal direction is perpendicular to the

1 reticle-side scan direction (+x direction), and the  
reticle R is scanned at a speed indicated by an arrow  
Vr in an exposure operation. The illumination area IA  
(whose center almost coincides with the optical axis  
5 IX) is projected on the wafer W through the projection  
optical system PL to form a projection area IA'. Since  
the wafer W and the reticle R have an inverted imaging  
relationship, the wafer W is scanned at a speed  
indicated by an arrow Vw in the opposite direction (-x  
10 direction) to the direction indicated by the arrow Vr  
in synchronism with the reticle R, thereby allowing the  
entire surface of a shot area SA of the wafer W to be  
exposed. A scan speed ratio Vw/Vr accurately  
corresponds to the reducing ratio of the projection  
15 optical system PL so that the pattern of a pattern area  
PA of the reticle R can be accurately  
reduced/transferred onto the shot area SA. The  
longitudinal dimension of the illumination area IA is  
set to be larger than that of the pattern area PA and  
20 smaller than the maximum width of a light-shielding  
area ST. By scanning the illumination area IA, the  
entire surface of the pattern area PA can be  
illuminated.

Referring to Fig. 1 again, the wafer W is  
25 vacuum-chucked on a wafer holder 17 and held on a wafer  
stage WST through the wafer holder 17. The wafer  
holder 17 can be inclined in an arbitrary direction

1 with respect to the optimum imaging plane of the  
projection optical system PL and can be finely moved  
along the optical axis IX (z direction) by a driver  
(not shown). In addition, the wafer stage WST is  
5 designed to be moved not only in the scan direction (x  
direction) but also in a direction (y direction)  
perpendicular to the scan direction to be arbitrarily  
moved to a plurality of shot areas so as to allow a  
step-and-scan operation. That is, the wafer stage WST  
10 repeats an operation of scanning/exposing a given shot  
area on the wafer W and an operation of moving to the  
next shot exposure start position. A wafer stage  
driver 18 constituted by a motor and the like serves to  
move the wafer stage WST in the X and y directions. A  
15 movable mirror 20 for reflecting a laser beam from an  
interferometer 19 is fixed to an end portion of the  
wafer stage WST. The X- and Y-positions of the wafer  
stage WST are always detected by the interferometer 19  
with a resolving power of about 0.01  $\mu\text{m}$ . Position  
20 information (or speed information) about the wafer  
stage WST is supplied to a wafer stage controller 21.  
The wafer stage controller 21 controls the wafer stage  
driver 18 on the basis of this position information (or  
speed information).

25 The wafer W which has been exposed and processed  
is aligned by a wafer alignment system (not shown) such  
that the projection image of the reticle is accurately

1 superposed and exposed on the wafer W. A detailed  
description of this operation will be omitted.

In the apparatus shown in Fig. 1, an oblique  
incident type wafer position detection system (focus  
5 detection system) constituted by a radiation optical  
system 22 and a reception optical system 23 is fixed to  
a support portion (column) 24 for supporting the  
projection optical system PL. The radiation optical  
system 22 radiates an imaging light beam for forming a  
10 pinhole or a slit image onto the optimum imaging plane  
of the projection optical system PL from a direction  
oblique to the optical axis IX. The reception optical  
system 23 receives a light beam, of the imaging light  
beam, which is reflected by the surface of the wafer W  
15 through a slit. The arrangement and the like of this  
wafer position detection system are disclosed in, e.g.,  
USP 4,650,983. The system is used to detect the  
positional deviation of the wafer surface in the  
vertical direction (z direction) with respect to the  
20 imaging plane so as to drive the wafer holder 17 in the  
z direction to keep a predetermined distance between  
the wafer W and the projection optical system PL.  
Wafer position information from the wafer position  
detection system is input to a focus position  
25 controller 25. This wafer position information is  
supplied to the wafer stage controller 21 through a  
main control system 100. The wafer stage controller 21

1 drives the wafer holder 17 in the z direction on the  
basis of the wafer position information.

Assume that in this embodiment, calibration of the  
wafer position detection system is performed in advance  
5 by adjusting the angle of a plane parallel glass (plane  
parallel) (not shown) arranged in the radiation optical  
system 22 such that the imaging plane becomes a zero  
reference. Alternatively, the inclination angle of a  
predetermined area on the wafer W with respect to the  
10 imaging plane may be detected by using a horizontal  
position detection system like the one disclosed in USP  
4,558,949, or by designing a wafer position detection  
system to detect focus positions at a plurality of  
arbitrary positions in the image field of the  
15 projection optical system PL (e.g., by forming a  
plurality of slit images in the image field).

A radiation amount sensor 41 is disposed on the  
wafer stage WST at almost the same level as that of the  
surface of the wafer W. The radiation amount sensor 41  
20 has a light-receiving surface which is at least larger  
than the projection area IA'. In measurement, the  
radiation amount sensor 41 is moved to a position  
immediately below the optical axis IX of the projection  
optical system PL, and outputs a signal Sc  
25 corresponding to the total intensity of illumination  
light passing through the reticle R. This signal Sc is  
used for initialization in correcting the imaging

1 characteristics which vary upon incidence of  
illumination light, as will be described in detail  
later.

5 The arrangement of the interferometer 19 will be  
described in detail below with reference to Fig. 3.  
Fig. 3 shows the detailed arrangement of components  
around the wafer stage WST. The interferometer 19 in  
this embodiment is constituted by five interferometers,  
i.e., X interferometers (interferometers  $19x_1$  and  $19x_2$ )  
10 for measuring the X-position of the wafer stage WST, Y  
interferometers (interferometers  $19y_1$  and  $19y_2$ ) for  
measuring the Y-position of the wafer stage WST, and an  
alignment interferometer  $19ya$  having an optical axis  
extending through a center  $OAc$  of an observation area  
15  $OA$  of an off-axis alignment system (not shown) in the y  
direction. The interferometers  $19x_1$  and  $19x_2$  are  
arranged to be symmetrical with respect to a straight  
line  $Cx$  extending through a center  $Ce$  of a projection  
field  $if$  of the projection optical system  $PL$  in a  
20 direction parallel to the X axis. A movable mirror  $20x$   
is an X-position detection movable mirror for  
reflecting laser beams from the interferometers  $19x_1$  and  
 $19x_2$ . The interferometers  $19y_1$  and  $19y_2$  are arranged to  
be symmetrical with respect to a straight line  $Cy$   
25 extending through the center  $Ce$  of the projection field  
 $if$  of the projection optical system  $PL$  in a direction  
parallel to the Y axis. A movable mirror  $20y$  is a

1 Y-position detection movable mirror for reflecting  
laser beams from the interferometers 19y<sub>1</sub> and 19y<sub>2</sub>. The  
wafer stage controller 21 incorporates a position  
calculator 21Xe for calculating an X-position, a yawing  
5 calculator 21Xθ for obtaining the yawing amount of the  
movable mirror 20x (wafer stage WST) from the Y-axis, a  
position calculator 21Ye for calculating a Y-position,  
a yawing calculator 21Yθ for obtaining the yawing  
amount of the movable mirror 20y (wafer stage WST) from  
10 the X-axis, and a position calculator 21Ya for  
calculating the Y-position of the off-axis alignment  
system at the center OAc. The position calculator 21Xe  
calculates an X-position measurement value Xe of the  
wafer stage WST on the basis of the average of  
15 measurement values obtained by the interferometers 19x<sub>1</sub>  
and 19x<sub>2</sub>. The yawing calculator 21Xθ calculates a  
yawing amount Xθ in the movement of the wafer stage WST  
in the x direction on the basis of the difference  
between the measurement values obtained by the  
20 interferometers 19x<sub>1</sub> and 19x<sub>2</sub>. The position calculator  
21Ye calculates a Y-position measurement value Ye of  
the wafer stage WST on the basis of the average of  
measurement values obtained by the interferometers 19y<sub>1</sub>  
and 19y<sub>2</sub>. The yawing calculator 21Yθ calculates a  
25 yawing amount Yθ in the movement of the wafer stage WST  
in the y direction on the basis of the difference

1 between the measurement values obtained by the  
interferometers 19y<sub>1</sub> and 19y<sub>2</sub>.

2 The position calculator 21Ya serves to measure a  
3 Y-position Ya of the wafer stage WST when a mark on the  
4 wafer W is to be detected by the off-axis alignment  
5 system. The alignment position measurement system (the  
interferometer 19ya and the position calculator 21Ya)  
6 is arranged to prevent an Abbe's error in a mark  
7 detecting operation which is caused when the  
8 observation center OAc of the off-axis alignment system  
9 is deviated from the center Ce of the projection field  
10 if of the projection optical system PL in the x  
direction. A reference plate FM having a reference  
11 mark formed thereon is arranged on the wafer stage WST.  
12 For example, the reference plate FM is used to measure  
13 the distance (baseline) between the observation center  
OAc of the off-axis alignment system and the center Ce  
14 of the projection field if of the projection optical  
system PL. The reference plate FM has a reflecting  
15 surface R<sub>2</sub> having a reflectance r<sub>2</sub>, and a reflecting  
16 surface R<sub>3</sub> having an almost zero reflectance. The  
17 surface of the radiation amount sensor 41 has a  
reflecting surface R<sub>1</sub> having a reflectance r<sub>1</sub>. The  
18 respective reflecting surfaces are used to obtain  
19 offset components or used as reference reflecting  
20 surfaces for calculating the reflectance of a wafer, as  
21 will be described later.

1       As shown in Fig. 3, the yawing amount of the wafer  
stage WST is independently measured by using both the  
X-axis movable mirror 20x and the Y-axis movable mirror  
20y. In this measurement, an averaging circuit 21k is  
5       used to average the yawing amounts  $X_0$  and  $Y_0$  measured  
by the two mirrors 20x and 20y. With this operation,  
variations in measurement value, obtained by the X-axis  
interferometers  $19x_1$  and  $19x_2$  and the Y-axis  
interferometers  $19y_1$  and  $19y_2$ , owing to air fluctuations  
10       in the respective laser beam paths are averaged,  
allowing measurement of a yawing amount with higher  
reliability.

      No significant problem is posed in the case of the  
wafer stage WST used for wafer exposure, as shown in  
15       Fig. 3. However, in the case of a stage for exposing a  
glass plate for the manufacture of a liquid crystal  
display element, the movement stroke of the stage may  
become extremely large in the X or y direction  
depending on the position of a projection image  
20       (pattern arrangement) on the glass plate. In this  
case, on the side where the movement stroke is  
extremely large, the laser beam path of one of a pair  
of interferometers for measuring yawing amounts may  
deviate from the movable mirror near the end point of  
25       the stroke. For this reason, it may be checked whether  
the laser beam path deviates from the movable mirror on  
the X- or Y-axis side depending on a pattern

1 arrangement (which can be known in design prior to  
exposure), and a yawing amount measured by the  
interferometer on the axis side where the laser beam  
path does not deviate from the movable mirror may be  
5 selectively used. As is apparent, when the laser beam  
paths of the interferometers on the two axis sides do  
not deviate from the movable mirrors, an average yawing  
amount obtained by the averaging circuit 21k is  
preferably used.

10 A beam splitter 26 for reflecting part (e.g., 5%)  
of the illumination light IL and transmitting the  
remaining part, is arranged in the optical path between  
the fly-eye lens 6 and the reticle R in the apparatus  
shown in Fig. 1. The beam splitter 26 guides light  
15 reflected by the reticle R to a reflected light sensor  
27. As the reflected light sensor 27, a photoelectric  
sensor such as a silicon photodiode or a  
photomultiplier is used. The reflected light sensor 27  
receives light reflected by the wafer W through the  
20 reticle R and outputs a signal Sb to the main control  
system 100. Since it is preferable that the reflected  
light sensor 27 receive light reflected by the entire  
illumination area IA (IA'), the reflected light is  
preferably focused by a lens or the like, or the  
25 reflected light sensor 27 is preferably disposed at a  
Fourier transform plane corresponding to the wafer W,

1 i.e., a position conjugate to the pupil position of the  
projection optical system PL.

The beam splitter 26 guides part of illumination  
light from the light source 1 to a photoelectric sensor  
5 28 for detecting the intensity of a light beam from the  
light source 1. The photoelectric sensor 28 receives  
part of the illumination light IL reflected by the beam  
splitter 26 and outputs an output signal Sa to the main  
control system 100.

10 The functions of the reflected light sensor 27 and  
the photoelectric sensor 28 will be described in detail  
later.

The apparatus of this embodiment also includes an  
input means 101 such as a keyboard or a bar code reader  
15 and hence can input various information, e.g., thermal  
time constant information about the projection optical  
system, transmittance information about the reticle R,  
an illumination slit width, a target exposure amount,  
and a scan speed.

20 The exit end face of the fly-eye lens 6, on which  
a plurality of two-dimensional light source images are  
formed, has a relationship of Fourier transform with  
the pattern area of the reticle R. An aperture stop 29  
for changing the shape of a two-dimensional light  
25 source is disposed near this exit end face. As the  
aperture stop 29, an annular aperture stop for limiting  
the shape of a two-dimensional light source image to an

1 annular shape, an aperture stop for limiting the shape  
of a two-dimensional light source image to a plurality  
of discrete areas decentered from the optical axis IX,  
or a circular aperture stop for changing the size of a  
5 two-dimensional light source image without changing the  
position of the center may be used. Annular aperture  
stops are disclosed in Japanese Laid-Open Patent  
Application No. 61-91662 and the like. As an aperture  
stop for limiting the shape of a two-dimensional light  
10 source image, for example, an aperture stop having four  
opening portions arranged to be point symmetrical about  
the optical axis IX is disclosed in detail in Japanese  
Laid-Open Patent Application No. 4-225514.

The apparatus shown in Fig. 1 includes a  
15 correction mechanism for correcting the imaging  
characteristics of the projection optical system PL.  
This correction mechanism for imaging characteristics  
will be described below.

As shown in Fig. 1, in this embodiment, the  
20 optical characteristics of the projection optical  
system PL itself and its projection image imaging  
characteristics can be corrected by independently  
driving the reticle R and lens elements 34 and 35 using  
an imaging characteristic controller 30. The reticle  
25 stage RST can be finely moved along the optical axis IX  
(in the vertical direction) by driving elements 31. As  
the driving elements 31, piezoelectric elements,

electrostrictive elements, or air dampers are used.  
Three or four driving elements 31 are used to drive the  
whole reticle stage RST.

Specifications of the imaging characteristics of  
5 the projection optical system PL (i.e., imaging  
characteristics of the image of a pattern of the reticle  
exposed to the wafer) include a focus position (imaging  
plane position), a projecting magnification, a distortion, a  
curvature of field, an astigmatism, and the like. These  
10 values can be independently corrected. In this embodiment,  
however, for the sake of a simple explanation, correction of a  
focus position, a projecting magnification, and a curvature of  
field in the double side telecentric projection optical system  
will be described below with reference to a method of driving  
15 the lens elements of the projection optical system PL.

The first group lens element 34 located nearest to  
the reticle R is fixed to a support member 36, and the  
second group lens element 35 is fixed to a support  
20 member 37. A lens element below a lens element 38 is  
fixed to a mirror barrel portion 39 of the projection  
optical system PL. Assume that in this embodiment, the  
optical axis IX of the projection optical system PL is  
the optical axis of the lens element fixed to the  
25 mirror barrel portion 39.

The support member 36 is coupled to the support  
member 37 through a plurality of (e.g., three; two are  
shown in Fig. 1) extendible driving elements 32. The

1 support member 37 is coupled to the mirror barrel  
portion 39 through a plurality of extendible driving  
elements 33.

In this arrangement, when the lens elements 34 and  
5 35 are translated along the optical axis, a projecting  
magnification (the enlargement/reduction amount of the  
size of a projection image) M, a curvature of field C,  
and a focus position F slightly change in amount at  
change rates corresponding to the moving amounts.

10 Letting  $z_1$  be the driving amount of the lens element 34  
and  $z_2$  be the driving amount of the lens element 35,  
variations  $\Delta M$ ,  $\Delta C$ , and  $\Delta F$  of the projecting  
magnification M, the curvature of field C, and the  
focus position F are expressed by the following  
15 equations, respectively:

$$\Delta M = C_{M1} \times z_1 + C_{M2} \times z_2 \quad \dots(1)$$

$$\Delta C = C_{C1} \times z_1 + C_{C2} \times z_2 \quad \dots(2)$$

$$\Delta F = C_{F1} \times z_1 + C_{F2} \times z_2 \quad \dots(3)$$

where  $C_{M1}$ ,  $C_{M2}$ ,  $C_{C1}$ ,  $C_{C2}$ ,  $C_{F1}$ , and  $C_{F2}$  are constants  
20 representing the change rates of variations with  
respect to the driving amounts of the respective lens  
elements.

As described above, the wafer position detection  
25 systems 22 and 23 serve to detect the shift amount of a  
wafer surface with respect to the optimum focus  
position, of the projection optical system PL, which  
serves as a zero reference. Therefore, when a proper

1 offset amount  $z_3$  is electrically or optically given to  
the wafer position detection systems 22 and 23, a focus  
position shift caused upon driving of the lens elements  
34 and 35 can be corrected by positioning the wafer  
5 surface using the wafer position detection systems 22  
and 23. In this case, equation (3) is rewritten as  
follows:

$$\Delta F = C_{F1} \times z_1 + C_{F2} \times z_2 + z_3 \quad \dots(4)$$

As described above, the variations  $\Delta M$ ,  $\Delta C$ , and  $\Delta F$   
10 can be arbitrarily corrected by setting the driving  
amounts  $z_1$  to  $z_3$  according to equations (1), (2), and  
(4). In this case, three types of imaging  
characteristics are simultaneously corrected. If,  
however, the variation in imaging characteristic, of  
15 the optical characteristics of the projection optical  
system, which is caused by absorption of illumination  
light is negligible, the corresponding correction  
described above need not be performed. In addition, in  
this embodiment, if an imaging characteristic other than  
20 the three types of imaging characteristics described  
above greatly changes, correction must be performed  
with respect to that imaging characteristic. In this  
embodiment, since the variation in curvature of field  
is corrected to zero or an allowable value or less, no  
25 special correction of the astigmatism is performed.

In this embodiment, the variation  $\Delta F$  in focus  
position (equation (4)) is corrected as follows. For

1 example, a proper offset amount is electrically or  
optically (using a plane parallel) given to the wafer  
position detection systems 22 and 23, and the wafer W  
is moved in the z direction by using the wafer position  
5 detection systems 22 and 23, thereby setting the  
surface of the wafer W at the optimum imaging plane  
(best focus position) of the projection optical system  
PL.

10 In this embodiment, the reticle R and the lens  
elements 34 and 35 are moved along the optical axis by  
the imaging characteristic controller 30. Especially  
the lens elements 34 and 35 greatly influence the  
respective characteristics associated with  
magnification, distortion, and curvature of field  
15 (astigmatism) and can be easily controlled, as compared  
with other lens elements. In this embodiment, the two  
groups of movable lens elements are arranged. However,  
three or more groups of lens elements may be arranged.  
In this case, the moving range of each lens element can  
20 be broadened while variations in other aberrations are  
suppressed. In addition, this arrangement can properly  
cope with various types of distortions (trapezoidal and  
rhombic distortions) and a curvature of field  
(astigmatism). Furthermore, distortions and the like  
25 can be corrected by driving the reticle R in the z  
direction.

1           Feedback control is also performed with respect to  
a predetermined target position by using position  
sensors for monitoring driving amounts, e.g., encoders,  
capacitive sensors, and reflection type sensors. When  
5   the above mechanism is to be used only for maintenance,  
even if dynamic correction is not performed during an  
exposure operation, the mechanism may be replaced with  
a fine feed mechanism with a micrometer head or a  
semi-stationary mechanism with a washer.

10           In the above imaging characteristic correction  
mechanism, correction is performed by moving the  
reticle R and the elements. However, this embodiment  
may use any proper correction mechanism of a different  
scheme other than that described above. For example,  
15   the following method may be used. A space defined by  
two lens elements or plane parallel glasses is sealed,  
and the pressure in the sealed space is adjusted. The  
apparatus shown in Fig. 1 includes a pressure control  
system 40 for adjusting the pressure in the sealed  
20   space defined by the lens elements so as to finely  
correct the optical characteristics (especially the  
magnification) of the projection optical system PL  
itself. The pressure control system 40 is also  
controlled by the imaging characteristic controller 30  
25   to provide desired imaging characteristics for a  
projection image. Since the detailed arrangement of

1 the pressure control system 40 is disclosed in USP  
4,871,237, a description thereof will be omitted.

As described above, variations in the imaging  
characteristics of the projection optical system PL  
5 owing to absorption of exposure light can be  
satisfactorily corrected by driving the lens elements  
or using the correction mechanism for adjusting the  
pressure in the sealed space defined by the lens  
elements.

10 A method of calculating a variation in imaging  
characteristic owing to absorption of exposure light  
will be described next. The above-described imaging  
characteristic correction mechanism is optimally driven  
on the basis of the calculated variation in imaging  
15 characteristic. Strictly speaking, variations in the  
above imaging characteristics need to be separately  
calculated. This is because the degrees to which the  
respective imaging characteristics are influenced  
slightly differ from each other depending on the lens  
20 elements constituting the projection optical system PL,  
and hence variation characteristics differ even if  
illumination light having the same energy is incident  
on the projection optical system PL. However, the  
basic calculation methods are the same, but the  
25 coefficients used in the calculations of the respective  
characteristics are slightly different from each other.  
Therefore, for the sake of simplicity, the following

1 description is made with reference to the variation  $\Delta M$   
in projecting magnification.

The principle of the method will be described  
first. The variation  $\Delta M$  in projecting magnification is  
5 caused because the refractive indexes or curvatures of  
the lens elements in the projection optical system PL  
slightly change when the lens elements slightly absorb  
illumination light and increase in temperature.  
Consider one lens element. Energy of illumination  
10 light is input to the lens element, i.e., heat is  
absorbed thereby, and at the same time, heat is  
dissipated to external components such as the mirror  
barrel portion 39. The temperature of the lens element  
is determined by the balance between the absorption and  
15 dissipation of heat. Providing that the temperature  
rise and the variation  $\Delta M$  in magnification are  
proportional to each other, it can be considered that  
the variation  $\Delta M$  in magnification is determined by the  
heat balance. In general, when the temperature of the  
20 lens element is low, absorption of heat is higher in  
rate than dissipation of heat, and hence the  
temperature gradually increases. When the temperature  
of the lens element becomes high as compared with the  
ambient temperature, dissipation of heat becomes higher  
25 in rate than absorption of heat. When the absorption  
of heat balances the dissipation of heat, the lens  
element reaches a saturation level to be set in an

1 equilibrium state. If an exposure operation is  
stopped, heat is gradually dissipated, and the  
temperature of the lens element decreases. When the  
difference between the temperature of the lens element  
5 and the ambient temperature becomes small, the speed of  
heat dissipation decreases. This characteristic is  
generally called a first-order time-lag, which can be  
expressed by a first-order differential equation.  
Figs. 4A and 4B show this state. Fig. 4A shows  
10 incident energy. Fig. 4B shows a magnification  
variation characteristic obtained when illumination  
light of a predetermined energy amount is radiated on  
the projection optical system PL for a predetermined  
period of time. The variation characteristic shown in  
15 Fig. 4B indicates a final variation  $\Delta M_1$  (saturation  
level) in projecting magnification with respect to  
radiation energy  $E_1$ . The variation  $\Delta M_1$  in projecting  
magnification can be determined by two values, i.e., a  
change rate  $\Delta M_1/E_1$  and a time constant  $T$  representing a  
20 change over time. Referring to Fig. 4B, the time  
constant  $T$  can be defined as a time during which the  
magnification changes by  $\Delta M_1 \times (1 - e^{-1})$  with respect to  
the final variation  $\Delta M_1$ . In this case, when the change  
rate  $\Delta M_1/E_1$  and the time constant  $T$  are obtained, the  
25 variation  $\Delta M$  in magnification can be calculated from an  
estimated value of the energy  $E$  which is incident on  
the projection optical system PL in accordance with the

1 output Sa from the photoelectric sensor 28. More  
specifically, by always monitoring the incident energy  
E, the variation  $\Delta M$  can be sequentially calculated in  
the main control system 100 on the basis of the change  
5 rate  $\Delta M_1/E_1$  and the time constant T. The change rate  
 $\Delta M_1/E_1$  and the time constant T can be obtained by  
checking a characteristic like the curve shown in  
Fig. 4B while experimentally keeping radiating  
illumination light on the projection optical system PL.  
10 In practice, however, since a plurality of lens  
elements are present in the projection optical system  
PL, the overall magnification variation characteristic  
is expressed by the sum of several first-order time-lag  
characteristics. The change rate  $\Delta M_1/E_1$  and the time  
15 constant T are input to the main control system 100  
through the input means 101. As described above, the  
change rate  $\Delta M_1/E_1$  and the time constant T are  
coefficients of a first-order differential equation.  
This differential equation is sequentially solved by  
20 numerical analysis using a general digital calculator  
or the like. In this case, if calculation  
synchronization is performed at predetermined time  
intervals sufficiently shorter than the time constant  
T, and the value of the energy E incident on the  
25 projection optical system PL is sequentially obtained  
(calculated) in accordance with this calculation

1   synchronization, the  $\Delta M$  at a given time point can be  
calculated by the main control system 100.

5   A method of obtaining different values of the  
incident energy  $E$  in accordance with the position of a  
reticle and obtaining the variation characteristic of  
an imaging characteristic in a case wherein the energy  
amount changes during an exposure operation for one  
shot will be described below.

10   A method of obtaining the energy  $E$  sequentially  
radiated on the projection optical system PL will be  
described below. When energy incident on the  
projection optical system PL is to be considered, the  
amount of light which is reflected by a wafer and  
incident on the projection optical system again must be  
15   considered in addition to the amount of light which is  
incident on the projection optical system PL through a  
reticle. In a scan type apparatus, since the reticle R  
is scanned with respect to the slit-like illumination  
area IA (i.e., the optical axis of the projection  
20   optical system), the total area of the light-shielding  
portion of the reticle R sequentially changes in  
accordance with the scan position, and the energy  $E$   
incident on the projection optical system PL changes in  
amount in accordance with the scan position of the  
25   reticle. For this reason, the incident energy  $E$  may be  
calculated by obtaining the sum of the amount of light  
which is incident on the projection optical system PL

1 through the reticle and the amount of light which is  
reflected by the wafer and incident on the projection  
optical system PL again, at time intervals  $\Delta t$  of, e.g.,  
several msec as sampling time intervals.

5 In this case, the amount of light which is  
incident on the projection optical system PL through  
the reticle is obtained on the basis of the output  $S_a$   
from the photoelectric sensor 28, and the amount of  
light which is reflected by the wafer and incident on  
10 the projection optical system PL again is obtained on  
the basis of the output  $S_b$  from the reflected light  
sensor 27. However, the output  $S_b$  from the reflected  
light sensor 27 includes light amount information about  
light reflected by the reticle R and optical members in  
15 the illumination optical system. For this reason, in  
this embodiment, reference reflection plates having  
different known reflectances are used, and reference  
reflection data for obtaining the reflection intensity  
of the wafer are obtained in accordance with the scan  
20 position of the reticle. The actual reflectance  
(reflection intensity) of the wafer is then obtained in  
accordance with the scan position of the reticle on the  
basis of the reference reflection data. In addition,  
the transmittance (transmitted light amount) of the  
25 reticle is obtained in accordance with the scan  
position of the reticle, and the energy  $E$  is obtained  
on the basis of these pieces of information.

1       A method of obtaining the incident energy E by  
using the wafer reflectance and the transmittance of  
the reticle which are obtained on the basis of the  
reference reflection data will be described next.

5       Letting P be the amount of light which is incident on  
the projection optical system PL through the reticle R,  
and r be the reflectance of the wafer W, the total  
amount of light incident on the projection optical  
system PL, including an amount  $P \cdot r$  of light which is  
10      reflected by the wafer W and incident on the projection  
optical system PL, can be expressed by equation (5):

$$E = P \times (1 + r) \quad \dots(5)$$

Letting  $\eta$  be the transmittance of the reticle R at  
the radiation position,  $I_p$  be the illuminance of a  
15      light source per unit area, and S be the radiation  
area, the light amount P can be expressed as follows:

$$P = I_p \times S \times \eta \quad \dots(6)$$

In this case, the illuminance  $I_p$  is the  
illuminance (without a reticle) on the wafer W per unit  
20      area, and the area S is the area of the projection area  
 $IA'$  of the wafer W for the sake of convenience. Since  
it is essential to obtain the relationship between the  
variation  $\Delta M$  and the energy E, the light amount P may  
be defined on the reticle R or any other places.

25      In performing a scan type exposure operation,  
since the amount of light which is incident on the  
projection optical system PL through the reticle R

1 changes in accordance with the position of the reticle  
R, the reticle transmittance  $\eta$  must be obtained for  
each scan position of the reticle R. A method of  
obtaining the transmittance of a reticle will be  
5 described below.

After the wafer stage WST is moved such that the  
radiation amount sensor 41 is located in the projection  
area IA', only the reticle stage RST is scanned while  
the wafer stage WST is fixed and the reticle R is  
10 placed on the reticle stage RST. At this time, the  
magnitude of an output  $Sc_1$  from the radiation amount  
sensor 41 is sequentially read in correspondence with  
the coordinate position ( $x_R$ ) of the interferometer 14  
for measuring the position of the reticle stage RST.  
15 Similarly, the magnitude of the output  $Sa$  from the  
photoelectric sensor 28 is read. A ratio  $Sc_1/Sa$  is then  
calculated and stored in a memory in the main control  
system 100 in correspondence with each coordinate  
position. For example, storage of such data in the  
20 memory (digital sampling) may be performed at intervals  
corresponding to a predetermined moving amount (e.g.,  
0.01  $\mu m$  to 10  $\mu m$ ) with reference to the resolving power  
(e.g., 0.01  $\mu m$ ) of the interferometer 14. In general,  
the main control system 100 is constituted by a digital  
25 computer. For this reason, in practice, several  
digital values of the ratio  $Sc_1/Sa$ , which are  
sequentially calculated with a resolving power almost

1 equal to the resolving power of the interferometer 14,  
may be averaged, and such average values may be stored  
at position intervals (or time intervals) at which no  
problem is posed in terms of an error in the  
5 calculation precision of a variation in magnification.  
Alternatively, the values of the ratio  $Sc_1/Sa$ , which are  
sequentially calculated with a resolving power almost  
equal to the resolving power of the interferometer 14  
(or a predetermined moving amount larger than that  
10 thereof).

Note that the position where the reticle stage RST  
starts to move so as to read the output  $Sc_1$  is stored,  
as a reference position for a read operation, in the  
main control system 100. An output  $Sc_2$  from the  
15 radiation amount sensor 41, reticle transmittance data  
 $\eta(x_R)$ , the output  $Sb$  from the reflected light sensor 27,  
reference reflectance data  $rx(x_R)$ , and offset component  
data, which output and data will be described later,  
are all stored in the memory with reference to this  
20 position.

A ratio  $Sc_2/Sa'$  (a constant value independent of  
the scan position) between the output  $Sc_2$  from the  
radiation amount sensor 41 and the output  $Sa$  from the  
photoelectric sensor 28, which are detected at the same  
25 timing before the reticle R is mounted on the reticle  
stage RST, is determined, and the data string  
(waveform) of the ratio  $Sc_1/Sa$  stored in the memory is

1 normalized (divided) by using the value of the  $Sc_2/Sa'$   
as a denominator. With this operation, the data string  
of a ratio  $Sc_1 \cdot Sa' / Sc_2 \cdot Sa$  output from the radiation  
amount sensor 41 in correspondence with the  
5 presence/absence of the reticle R is obtained. The  
data string of this ratio is stored in the memory at  
the same intervals as the digital sampling intervals  
for the output  $Sc_1$ . This output ratio  $Sc_1 \cdot Sa' / Sc_2 \cdot Sa$  is  
the true reticle transmittance  $\eta$  obtained by correcting  
10 a detection error due to fluctuations in the  
illuminance  $I_p$ . Since the transmittance  $\eta$  is a  
function of the position  $x_R$ , it can be expressed as  
 $\eta(x_R)$ . For example, this function can be expressed by  
the curve shown in Fig. 5. Referring to Fig. 5, the  
15 abscissa indicates the position  $x_R$  of the reticle in the  
x direction (scan direction); and the ordinate represents the  
reticle transmittance  $\eta$ . Since the position  $x_R$  changes  
with time  $t$  during a scan operation,  $\eta(x_R) = \eta(t)$ ,  
20 provided that the scan operation is performed at a  
constant speed. The illuminance  $I_p$  is a factor which  
varies with time. For this reason, in an actual  
scan/exposure operation, equation (6) is modified to  
equation (7), and the illuminance  $I_p$  during the  
25 scan/exposure operation is sequentially obtained from  
the output  $Sa$  from the photoelectric sensor 28 and  
substituted into equation (7):

$$P(t) = S \times \eta(t) \times I_p(t) \quad \dots(7)$$

1            $\eta(t) = \eta(x_R)$

          If the illuminance  $I_p$  does not change with time  
(for example, if a mercury discharge lamp or the like  
is used as a light source), a variation in the  
5   illuminance  $I_p$  during an exposure operation with  
respect to one shot area on the wafer  $W$  can almost be  
neglected. Therefore, the illuminance  $I_p$  may be  
detected on the basis of the output  $S_a$  from the  
photoelectric sensor 28 and stored immediately before a  
10   scan/exposure operation is started, and  $I_p(t)$  can be  
used as a constant in calculating equation (7). In  
this case, the illuminance  $I_p$  may be treated as a  
constant value when the shutter is turned on by a  
shutter ON/OFF signal, whereas the illuminance  $I_p$  may  
15   be treated as  $I_p = 0$  when the shutter is turned off.  
In addition, since an output from the radiation amount  
sensor 41 indicates the incident light amount  $P(t)$ , the  
incident light amount  $P(t)$  measured before an exposure  
operation can be used without registering  $\eta(t)$  for each  
20   reticle in advance. In any case, since the time  $t$  in  
equation (7) uniquely corresponds to the scan position  
of the reticle (or the wafer), the incident light  
amount  $P(t)$  is obtained in real time by reading out the  
transmittance data  $\eta(x_R)$  from the memory in accordance  
25   with the measurement position  $x_R$  of the interferometer  
14.

1           Furthermore, since the radiation amount sensor 41  
is allowed to have a small light-receiving area as  
compared with a batch exposure type sensor for  
illuminating the entire reticle surface at once, an  
5   inexpensive, uniform sensor (a silicon photodiode or  
the like) having almost no illuminance irregularity on  
the light-receiving surface can be used as the  
radiation amount sensor 41. If the light source 1 is a  
pulse light source, the radiation amount sensor 41  
10   receives pulse light. In this case, the radiation  
amount sensor 41 may measure the intensity of each  
pulse triggered in accordance with the scan position of  
the reticle R, and the resulting output  $S_c$  may be  
sequentially loaded as the illuminance  $I_p$ .  
15   Alternatively, the intensities of pulse light (one or a  
plurality of pulses) triggered in a predetermined short  
period of time, e.g., several to several tens of msec may  
be accumulated, and the average illuminance  $I_p$  for each  
period time may be sequentially loaded.

20           A method of obtaining the reflectance  $r$  in  
equation (5) will be described next.

As described above, in addition to light reflected  
by the wafer W surface, light reflected by the reticle  
R surface or each lens element of the projection  
25   optical system PL is incident on the reflected light  
sensor 27. For this reason, the actual wafer  
reflectance is calculated in accordance with reference

1 reflection data prepared by using reference reflecting  
surfaces on the wafer stage WST. Assume that the  
surface of the radiation amount sensor 41 is the  
reflecting surface  $R_1$  having the known reflectance  $r_1$ ,  
5 and the surface of the reference plate FM is the  
reflecting surface  $R_2$  having the known reflectance  $r_2$ .  
The reflectances  $r_1$  and  $r_2$  ( $r_1 > 0$ ;  $r_2 > 0$ ) corresponding  
to illumination light for exposure at two reference  
reflecting surfaces are known values measured in  
10 advance, and it is preferable that the two reflectances  
 $r_1$  and  $r_2$  be greatly different from each other. First,  
the wafer stage WST is moved such that the reflecting  
surface  $R_1$  is located within the projected radiation  
area  $IA'$  while the reticle R is set. The reticle stage  
15 RST is then moved at a predetermined speed while the  
wafer stage WST is at rest. With this operation, the  
magnitude of an output  $I_1$  from the reflected light  
sensor 27 is digitally sampled for each scan position  
of the reticle R, and the sampled data are sequentially  
20 stored in the memory of the main control system 100 in  
correspondence with the respective scan positions.  
Digital sampling and storage in the memory may be  
performed at intervals corresponding to a predetermined  
moving amount with reference to, e.g., the resolving  
25 power (e.g.,  $0.01 \mu\text{m}$ ) of the interferometer 14. In  
this case, the digital sampling interval need not

1 coincide with the resolving power of the interferometer  
14 and may be larger than that, e.g.,  $0.2\text{ }\mu\text{m}$  to  $10\text{ }\mu\text{m}$ .

Subsequently, the wafer stage WST is moved such  
that the reflecting surface  $R_2$  having the reflectance  $r_2$   
5 is located within the radiation area  $IA'$ . The reticle  
stage RST is then moved at a predetermined speed while  
the wafer stage WST is at rest. With this operation,  
the magnitude of an output  $I_2$  from the reflected light  
sensor 27 is sequentially stored (digitally sampled) in  
10 the memory of the main control system 100 in accordance  
with each position of the reticle R. In this case, the  
timing of storage in the memory is set to be equal to  
the digital sampling interval for the output  $I_1$ , and  
addresses in the memory are set so that the sampling  
15 positions of the outputs  $I_1$  uniquely correspond to those  
of the outputs  $I_2$ .

Especially when the light source 1 is a pulse  
light source, the values of the outputs  $I_1$  and  $I_2$  must  
be normalized ( $I_1/Sa$ ;  $I_2/Sa$ ) by using the output  $Sa$  from  
20 the photoelectric sensor 28 to correct an intensity  
variation of each pulse. This equally applies to the  
case wherein an ultraviolet line from a mercury  
discharge lamp is used as illumination light. The  
normalized values  $I_1/Sa$  and  $I_2/Sa$  are stored in the  
25 memory.

Fig. 6 shows the relationship between the output  
of light reflected by each reference reflecting surface

1 and the reflectance. Referring to Fig. 6, the values  $I_1$   
and  $I_2$  (or  $I_1/S_a$  and  $I_2/s_a$ ) sampled when the reticle R  
is moved to a given scan position are plotted along the  
ordinate, and the reflectance is plotted along the  
5 abscissa. As shown in Fig. 6, by drawing a straight  
line passing coordinates  $(r_1, I_1)$  and  $(r_2, I_2)$ , a  
reflectance (more accurately, reflection intensity)  $rx$   
of the wafer can be obtained from an output value from  
the reflected light sensor 27 which is obtained at this  
10 scan position. That is, if the output from the  
reflected light sensor 27, obtained when the reticle R  
is moved to the scan position during an actual exposure  
operation, is represented by  $I_x$ , the wafer reflectance  
 $rx$  at this time can be calculated according to the  
15 following equation by reading out the values  $I_1$  and  $I_2$   
as the reference reflection data in the memory which  
correspond to the scan position.

$$rx = [(r_2 - r_1)/(I_2 - I_1)] \times (I_x - I_1) + r_1 \quad \dots(8)$$

For example, a method of using three reference  
20 reflecting surfaces having different reflectances and  
obtaining the straight line shown in Fig. 6 from three  
measurement points by the least square approximation  
may be used. In this case, the area of each reference  
reflecting surface is allowed to be small as compared  
25 with a batch type sensor. When the reflected light  
sensor 27 is to receive pulse light, the intensity of  
each pulse may be measured, or power may be accumulated

1 for a predetermined short period of time, e.g., several  
to several tens of msec, so as to be output as average  
power. In any case, the data strings of the outputs  $I_1$   
and  $I_2$  are stored in the memory before an actual  
5 exposure operation. Alternatively, equation (8) may be  
prepared as reference reflection data at each scan  
position (sampling position) of the reticle R and  
stored in the memory. As is apparent, when the outputs  
 $I_1$  and  $I_2$  are normalized by using the output  $S_a$ , the  
10 output  $I_x$  from the reflected light sensor 27, used to  
obtain the actual wafer reflectance  $r_x$ , is also  
normalized by using the output  $S_a$  and substituted into  
equation (8).

Fig. 7A shows examples of reference reflection  
15 data prepared as outputs  $I_1(x_R)$  and  $I_2(x_R)$  from the  
reflected light sensor 27, obtained at each scan  
position of a reticle on the basis of light reflected  
by the reference reflecting surfaces, and an output  
 $I_x(x_R)$  from the reflected light sensor 27, obtained at  
20 each position of the reticle on the basis of light  
reflected by the wafer W during an exposure operation.  
Referring to Fig. 7A, the ordinate represents the  
intensity  $I_x$  of reflected light; and abscissa represents the  
position  $x_R$  of the reticle in the  $x$  direction. Assume  
25 that the reticle R is scanned from a position  $x_{R1}$  to a  
position  $x_{R2}$ . For example, reflectance data  $r_x(x_R)$   
corresponding to the scan position of the reticle is

1 calculated according to equation (9) based on equation  
(8) on the basis of the output  $I_x(x_R)$  from the reflected  
light sensor 27, obtained during an actual exposure  
operation with respect to the first shot area on the  
5 wafer W, the pre-stored data  $I_1(x_R)$  and  $I_2(x_R)$ , and fixed  
constants  $r_1$  and  $r_2$ . The reflectance data  $rx(x_R)$  are  
stored in the memory at the same sampling intervals as  
the digital sampling intervals for the outputs  $I_1(x_R)$   
and  $I_2(x_R)$  and at addresses uniquely corresponding to  
10 the respective scan positions. Fig. 7B shows the  
reflectance data  $rx(x_R)$  corresponding to the position of  
the reticle. Referring to Fig. 7B, the ordinate  
represents the wafer reflectance; and the abscissa represents the  
scan position  $x_R$  of the reticle in the x direction.

15

$$rx(x_R) = [(r_2 - r_1)/(I_2(x_R) - I_1(x_R))] \times$$
$$(I_x(x_R) - I_1(x_R)) + r_1 \quad \dots(9)$$

Since the position  $x_R$  changes with time, if the  
reticle stage RST is moving at a constant speed during  
an actual exposure operation, the reflectance data  
20  $rx(x_R)$  can be replaced with  $rx(t)$ . Therefore, by  
substituting equations (7) and (9) into equation (5),  
an energy value  $E(t)$  is calculated by the main control  
system 100 at the predetermined time intervals  $\Delta t$ .

25 Calculation of the energy E incident on the  
projection optical system PL and calculation of a  
variation in imaging characteristic of the projection  
optical system PL will be described next with reference

1 to Figs. 8A and 8B. In this case, for the sake of a  
simple explanation, the variation  $\Delta M$  in magnification  
of the projection optical system PL will be described  
hereinafter. Fig. 8A is a graph showing an amount E of  
5 light incident on the projection optical system PL,  
more specifically energies  $E_a$ ,  $E_b$ , and  $E_c$  incident on  
the projection optical system PL. Referring to  
Fig. 8A, the instantaneous value or average value of  
incident energy, obtained at the position of the  
10 reticle stage RST at the predetermined time intervals  
 $\Delta t$  (e.g., several msec to several tens of msec) is defined  
as the incident energy E. In Fig. 8A, predetermined  
timings (to be referred to as sampling timings  
hereinafter) at the predetermined time intervals  $\Delta t$  are  
15 denoted by reference symbols  $t_1$ ,  $t_2$ ,  $t_3$ ,  $t_4$ , and  $t_5$ ,  
respectively, and the corresponding positions of the  
reticle stage RST are denoted by reference symbols  $x_1$ ,  
 $x_2$ ,  $x_3$ ,  $x_4$ , and  $x_5$ , respectively. It is preferable that  
measurement of a sampling time be started when the  
20 reticle stage RST reaches the reference position set in  
storing each type of data described above, and the  
positions  $x_1$  to  $x_5$  coincide with the positions where the  
respective types of data are stored in the memory. As  
is apparent, the reticle stage RST is controlled to  
25 attain a predetermined speed before it reaches this  
reference position.

1       The main control system 100 calculates energy  $E(t_1)$   
=  $E_a$  which is incident on the projection optical system  
PL at the sampling timing  $t_1$ , as an estimated value, on  
the basis of a transmittance  $\eta(x_1)$ , a reflectance  
5        $rx(x_1)$ , an illuminance  $I_p(t_1)$ , and the radiation area  
(determined by the reticle blind 8)  $IA'$  on the wafer W  
at the sampling timing  $t_1$  and the position  $x_1$  of the  
reticle stage RST, according to equations (5), (7), and  
(9). As described above, if a mercury discharge lamp  
10       or the like is used as a light source, opening/closing  
information about the shutter 2 (a weight of "1" is set  
if the shutter is open; and a weight of "0", if it is  
closed) and  $I_p(t)$  for  $I_p$  = a constant value can be  
handled as a constant. Note that if the position  $x_1$   
15       where the transmittance  $\eta(x_1)$  and the reflectance  $rx(x_1)$   
are stored does not correspond to the sampling timing  
 $t_1$ , a transmittance  $\Delta(x_R)$  and a reflectance  $rx(x_R)$   
stored at a position  $x$  nearest to the position  $x_1$  after  
the sampling timing  $t_1$  may be used. The opening/closing  
20       information (1 or 0) about the shutter 2 may be used as  
follows. If the information indicates that the shutter  
2 is open at a sampling timing, calculations are  
executed by using equations (5), (7), and (9) to obtain  
25        $E(t_1) = E_a$ . If the information indicates that the  
shutter is closed,  $E(t_1) = 0$  is set without performing  
calculations according to equations (5), (7), and (9).

1 Incident energies are obtained at the sampling  
timings  $t_2$  to  $t_5$  in the same manner as described above.  
In this case, the incident energy  $E_a$  is obtained at the  
sampling timings  $t_1$  and  $t_3$ ; the incident energy  $E_b$  is  
5 obtained at the sampling timings  $t_2$  and  $t_5$ ; and the  
incident energy  $E_c$  is obtained at the sampling timing  
 $t_4$ .

Note that an incident energy may be obtained by  
using the average value of data obtained at the  
10 sampling time intervals  $\Delta t$  (e.g., in the time interval  
between the sampling timings  $t_1$  and  $t_2$ ). Assume that  
the digital sampling interval for the transmittance  
data  $\eta(x_R)$  and the reflectance data  $rx(x_R)$  is set to be  
25  $\mu m$  on the reticle; the sampling time interval  $\Delta t$   
15 between the sampling timings  $t_1$  and  $t_2$  is set to be 5  
msec; and a scan speed  $V$  is set to be 50 mm/sec. In  
this case, a distance  $L$  the reticle stage moves in the  
sampling time interval  $\Delta t$  is expressed as  $L = V \times \Delta t =$   
250  $\mu m$ . Since the digital sampling interval for the  
20 transmittance data  $\Delta(x_R)$  and the reflectance data  $rx(x_R)$   
is 25  $\mu m$ , 10 transmittance data  $\eta(x_R)$  and 10 reflectance  
data  $rx(x_R)$  are obtained as sampled data in the sampling  
time interval  $\Delta t$  between the sampling timings  $t_1$  and  $t_2$ .  
25 Hence, the 10 transmittance data  $\eta(x_R)$  and the 10  
reflectance data  $rx(x_R)$  as the sampled data may be  
averaged, respectively, and the resultant data may be  
used as average transmittance data  $\eta(x_2)$  and average

1 reflectance data  $rx(x_2)$  at the sampling timing  $t_2$ .  
Subsequently, energy  $E(t_2) = E_b$  which is incident on the  
projection optical system PL at the sampling timing  $t_2$   
is calculated as an estimated value on the basis of a  
5 transmittance  $\eta(x_2)$ , a reflectance  $rx(x_2)$ , an  
illuminance  $I_p(t_2)$ , opening/closing information about  
the shutter 2 (a weight of "1" is set if the shutter is  
open; and a weight of "0", if it is closed), and the  
area of a radiation area (determined by the reticle  
10 blind 8) on the wafer W at the sampling timing  $t_2$ ,  
according to equations (5), (7), and (9). As described  
above, in this case, if the light source 1 is a light  
source for emitting pulse light, power in the sampling  
time interval  $\Delta t$ , as a unit time, between the sampling  
15 timings and  $t_1$  and  $t_2$  may be accumulated, and the  
resultant value may be used as average power  $I_p(t_2)$   
within the unit time. With regard to the digital  
sampling interval for the transmittance  $\eta(x_R)$  and the  
reflectance  $rx(x_R)$ , since a resolving power smaller than  
20 the distance L the reticle stage moves in the sampling  
time interval  $\Delta t$  is required, the sampling time  
interval  $\Delta t$  is set such that the distance L becomes  
smaller than the width of the illumination area IA in  
the scan direction. Note that after the first shot,  
25 the incident energy E may be obtained by using the  
reflectance data  $rx(x_R)$  stored in the memory when the

1 first shot exposure is performed, without obtaining the  
reflectance  $rx(x_R)$  according to equation (9).

Calculation of a variation in optical  
characteristic of the projection optical system PL on  
5 the basis of the amount of incident energy per unit  
time will be described further with reference to  
Fig. 8B. Fig. 8B shows a magnification variation  
characteristic  $\Delta M$ s with respect to the incident energy  
E. As shown in Fig. 8B, the magnification variation  
10 characteristic with respect to the incident energy E is  
dependent on  $\Delta M/E$  and the time constant T, as in the  
case shown in Fig. 4B. Therefore, a variation in  
magnification with respect to incident energy at a  
position corresponding to each time (a predetermined  
15 time interval) can be obtained from the magnification  
variation characteristic determined by  $\Delta M/E$  and the  
time constant T, like the one shown in Fig. 4B.

This operation will be described in detail below  
with reference to Fig. 8B. The variation  $\Delta M_1$  in  
20 magnification, caused by the energy  $E_a$  between the  
sampling timings  $t_0$  and  $t_1$  is obtained from  $\Delta M/E$ . As  
described above,  $\Delta M/E$  is obtained in advance by an  
experiment or the like. Similarly, a variation  $\Delta M_3$  in  
magnification, caused by the energy  $E_b$  between the  
25 sampling timings  $t_1$  and  $t_2$  is obtained from  $\Delta M/E$ . The  
reduction rate of the magnification between the  
sampling timings  $t_1$  and  $t_2$  is determined by the thermal

1 time constant  $T$  so that the reduction amount of the  
magnification which reduced with time in accordance  
with the time constant  $T$  can be obtained from the  
initial value ( $\Delta M_1$  in this case) between the sampling  
5 timings  $t_1$  and  $t_2$ . Therefore, the variation in  
magnification at the sampling timing  $t_2$  is the value  
obtained by subtracting the reduction amount between  
the sampling timings  $t_1$  and  $t_2$  from the sum of  $\Delta M_1$  and  
 $\Delta M_2$ . Similarly, a variation  $\Delta M_3$  in magnification,  
10 caused by the energy  $E_a$  between the sampling timings  $t_2$   
and  $t_3$ , a variation  $\Delta M_4$  in magnification, caused by the  
energy  $E_c$  between the sampling timings  $t_3$  and  $t_4$ , and a  
variation  $\Delta M_5$  in magnification, caused by the energy  $E_b$   
15 between the sampling timings  $t_4$  and  $t_5$ , can be obtained  
from  $\Delta M/E$ . The reduction amount in each sampling  
interval is obtained in the same manner as described  
above, and the final variation in magnification at each  
sampling timing can be obtained. As a result, an  
20 envelope connecting the values at the respective  
sampling timings can be obtained as a magnification  
variation characteristic, as shown in Fig. 8B. Such  
calculation methods of sequentially obtaining a  
magnification variation characteristic from discrete  
25 magnification variation values are disclosed in USP  
4,666,273 and USP 4,920,505.

A method of correcting a magnification will be  
described next.

1       The imaging characteristic controller 30  
determines the control amount of the pressure control  
system 40 and the driving amounts of the driving  
elements 31, 34, and 35 so as to change the  
5       magnification in accordance with the magnification  
variation characteristic shown in Fig. 8B, thereby  
correcting the magnification. Note that the imaging  
characteristic controller 30 is exclusively used to  
adjust the magnification M in a direction perpendicular  
10      to the scan direction, and the magnification in the  
scan direction must be corrected by slightly changing  
the moving speed of the reticle R relative to the wafer  
W. Therefore, the relative speed must be finely  
adjusted in accordance with the adjusting amount of  
15      magnification corrected by the imaging characteristic  
controller 30 to isotopically change the size of a  
projection image on the entire surface of a shot area.

      The above description is associated with the  
method of correcting a variation in magnification.  
20      Other imaging characteristics can be corrected in the  
same manner as described above. Note that the pattern  
of the reticle R is sequentially exposed on the wafer W  
a plurality of                   times. In order to improve  
the productivity, exposure may be performed by  
25      alternately scanning the wafer stage WST (reticle stage  
RST) in opposite directions in units of shot arrays on  
the wafer instead of scanning the stage in one

1 direction all the time. That is, in some cases, after  
one shot array is exposed, another shot array is  
exposed while the stage is scanned in the opposite  
direction (i.e., exposure is performed while the stage  
5 is reciprocated). The transmittance data  $\eta$ , the  
reference reflectance data, and the like described  
above are stored or calculated in accordance with the  
position of the reticle R while the reticle R is moved  
in one direction (e.g., in the -x direction). For this  
10 reason, if the scan direction of the wafer stage WST is  
alternately reversed in units of shot arrays on a wafer  
(the scan direction of the reticle stage RST  
alternately changes to the -x direction and +x  
direction), the read direction of the transmittance  
15 data  $\eta$ , the reflectance data, and the like is switched  
in accordance with the scan direction. That is, when a  
scan operation is to be performed in a direction  
opposite to the scan direction, of the reticle stage  
RST, in which the transmittance data  $\eta$  and the  
20 reference reflectance data are stored, the  
transmittance data  $\eta$ , the reference reflectance data,  
and the like are read out from the memory in the  
opposite direction.

In this case, equations (5) and (6) may be used  
25 without any modification by obtaining an average  
transmittance and an average reflectance during a scan  
operation. In this method, however, an average

1 transmittance and an average reflectance in one scan  
operation can only be treated as average values, and a  
reflectance can be calculated only after one scan  
operation, resulting in a deterioration in precision.

5 Whether a deterioration in precision due to this method  
falls within an allowable range is determined in  
consideration of the precision required to calculate  
the variation  $\Delta M$  in magnification, the variation  $\Delta M$  in  
magnification in one scan operation, the comparison

10 between the time required for one scan operation and  
the time constant  $T$ , a change in the transmittance  $\eta$  of  
the reticle  $R$  with a change in the position of the  
reticle  $R$ , and a change in the reflectance  $r$  of the  
wafer  $W$  with a change in the position of the reticle  $R$ .

15 However, the time required for one scan operation is  
dependent on the sensitivity of a resist, and the  
uniformity of the transmittance and the like of a  
reticle to be used are indefinite factors. Therefore,  
in this embodiment, the intensity of light reflected by

20 a wafer is obtained on the basis of reference  
reflectance data prepared on the basis of the intensity  
of light reflected by each reference reflecting surface  
in accordance with the scan position of a mask. With  
this operation, even if the intensity of reflected

25 light changes in accordance with the position of the  
reticle, a correct reflectance can be obtained by  
scanning the reticle during an exposure operation.

1           The second embodiment of the present invention  
will be described next. The second embodiment is  
different from the first embodiment in the following  
point. In the second embodiment, light amount  
5   information (to be referred to as an offset component  
hereinafter) about light reflected by a reticle R or an  
optical member in an illumination optical system is  
stored in a memory in correspondence with the position  
of the reticle R, without obtaining reference  
10   reflectance data by using reference reflecting  
surfaces, and a value obtained by subtracting the  
offset component from an output  $S_b$  from a reflected  
light sensor 27 is used as the amount of light which is  
reflected by a wafer and incident on a projection  
15   optical system PL again. The same reference numerals  
in the second embodiment denote the same parts as in  
the first embodiment. In addition, in this embodiment,  
information required to obtain the amount of light  
(light energy) which is incident on the projection  
20   optical system PL through a reticle, i.e., information  
about the transmittance of the reticle (in this  
embodiment, the transmittance is the ratio of the  
amount of light in an illumination area IA to the  
amount of light which is not shielded by the  
25   light-shielding portion of a pattern but is transmitted  
therethrough) is detected on the basis of outputs from

1 a radiation amount sensor 41 and a light source sensor  
28.

A case wherein the amount of light which is  
incident on the projection optical system PL through a  
5 reticle is obtained will be described below.

A main control system 100 stores a ratio  $Sc/Sa$  of  
an output  $Sc$  from the radiation amount sensor 41 to an  
output  $Sa$  from the light source sensor 28 in an  
internal memory in synchronism with an operation of  
10 moving a reticle stage RST, on which the reticle R is  
mounted, by a distance corresponding to one scan  
operation. That is, the main control system 100 moves  
the reticle stage RST (while keeping a wafer stage WST  
at rest); converts the ratio  $Sc/Sa$  of the output  $Sc$   
15 from the radiation amount sensor 41 to the output  $Sa$   
from the light source sensor 28 into a time-series  
digital value in accordance with the position of the  
reticle stage RST which is detected by a interferometer  
14; and stores the digital value in the internal  
20 memory. This ratio data becomes information  
corresponding to a variation in transmittance in a  
reticle scan operation. This ratio is denoted by  
reference symbol  $Rh$ . As described above, storage of  
data in the memory (digital sampling) may be performed  
25 for each predetermined moving amount (e.g.,  $0.01\ \mu m$  to  
 $10\ \mu m$ ) with reference to the resolving power (e.g.,  
 $0.01\ \mu m$ ) of the interferometer 14. The variable ratio

1 Rh of the output  $S_c$  from the radiation amount sensor 41  
to the output  $S_a$  from the light source sensor 28,  
obtained at each stored position of the reticle stage  
RST, is stored in the memory in correspondence with  
5 each position of the reticle stage RST. In an actual  
exposure operation, the ratio  $R_h$  stored in the memory  
in advance in correspondence with each position of the  
reticle stage RST at predetermined time intervals,  
e.g., about several msec, is read out, and a value  
10 ( $S_a \cdot R_h$ ) obtained by multiplying the output  $S_a$  from the  
photoelectric sensor 28 in the actual exposure  
operation (the output value from the photoelectric  
sensor 28 at the predetermined time intervals) by the  
read value is used as an estimated value of the amount of  
15 light (energy) which is incident on the projection  
optical system PL through the reticle at the  
predetermined time intervals. Since the main control  
system 100 is constituted by a general digital  
computer, the ratios  $R_h$  or the products  $S_a \cdot R_h$  may be  
20 averaged, and the average value may be stored, similar  
to digital sampling of various types of data in the  
first embodiment. Alternatively, the ratios  $R_h$  or the  
products  $S_a \cdot R_h$  sequentially calculated with a resolving  
power almost equal (or lower than) the resolving power  
25 of the interferometer 14 may be stored without any  
modification.

1           Detection of information about the amount of light  
reflected by a wafer will be described below.

When energy incident on the projection optical  
system PL is to be considered, the amount of light  
5   which is reflected by a wafer and incident on the  
projection optical system PL again must be considered  
in addition to the amount of light which is incident on  
the projection optical system PL through a reticle.  
For this reason, the amount of light which is reflected  
10 by a wafer and incident on the projection optical  
system PL again is detected on the basis of the output  
Sb from the reflected light sensor 27. The main  
control system 100 moves the reticle stage RST by a  
distance corresponding to one scan operation while the  
15 reticle R is mounted on the stage, and stores  
(digitally samples) the time-series photoelectric  
signal Sb (light amount information) from the reflected  
light sensor 27 in the memory in accordance with the  
position of the reticle stage RST which is detected by  
20 the interferometer 14. For example, storage of data in  
the memory may be performed for each predetermined  
moving amount with reference to the resolving power  
(e.g., 0.01  $\mu\text{m}$ ) of the interferometer 14. In this  
case, the digital sampling interval need not coincide  
25 with the resolving power of the interferometer 14 and  
may be set to be larger than that, e.g., 0.2  $\mu\text{m}$  to 10  
 $\mu\text{m}$ .

1           The output Sb from the reflected light sensor 27  
includes information about the amount of light  
reflected by the reticle R and optical members in the  
illumination optical system. For this reason, the  
5   reticle R is scanned after the reference reflecting  
surface of a reference plate FM having a reflecting  
surface having an almost zero reflectance is located  
within a projection area IA' of the projection optical  
system PL. In this scan operation, reflected light is  
10   received by the reflected light sensor 27, and a  
variation in the output Sb is stored in the memory in  
accordance with the position of the reticle stage RST.  
The stored data is used as information about the amount  
of light reflected by the reticle R and optical members  
15   in the illumination optical system. This information  
will be referred to as an offset component hereinafter.  
In an actual exposure operation, the stored offset  
component may be subtracted from the output value Sb  
from the reflected light sensor 27.

20           In the above case, if the photoelectric sensor 28,  
the radiation amount sensor 41 and the reflected light  
sensor 27 are to receive pulse light, the intensity of  
each pulse may be detected, or power in a short period  
of time, e.g., a unit time of several to several tens of  
25   msec, may be accumulated, and the resultant value may  
be output as average power in the unit time.

1           Calculation of an amount E of light incident on  
the projection optical system PL will be described next  
with reference to Figs. 8A and 8B.

          The amount E of light incident on the projection  
5   optical system PL and a variation in imaging  
characteristic of the projection optical system PL can  
be obtained in the same manner as in the first  
embodiment. This operation will be briefly described  
below. In this embodiment, reference symbols Ea, Eb,  
10   and Ec in Fig. 8A denote the sums of the amounts of  
light incident on the projection optical system PL from  
the reticle side and the amounts of light incident on  
the projection optical system PL again from the wafer  
side, with the position of the reticle stage RST being  
15   used as a variable. The main control system 100  
detects the output Sa from the photoelectric sensor 28  
and the output Sb from the reflected light sensor 27 at  
a sampling timing  $t_1$ . The main control system 100 reads  
out the output Sa obtained the photoelectric sensor 28  
20   at a position  $x_1$  corresponding to the sampling timing  
 $t_1$ , the ratio Rh obtained by the radiation amount sensor  
41, and an offset component from the memory. The main  
control system 100 adds the product of the output Sa  
from the photoelectric sensor 28 and the ratio Rh to a  
25   value obtained by subtracting the offset component  
corresponding to the position  $x_1$  (or the timing  $t_1$ ) from  
the output Sb from the reflected light sensor 27. The

1 main control system 100 then calculates an estimated  
value of energy  $E_a$  incident on the projection optical  
system PL at the sampling timing  $t_1$  on the basis of  
opening/closing information about a shutter 2 (a weight  
5 of "1" is set if the shutter is open; and a weight of  
"0", if it is closed), and the area of a radiation area  
(determined by a reticle blind 8)  $IA'$  on the wafer W.

Note that if the position  $x_1$  where the ratio  $R_h$  and  
the offset component are stored does not correspond to  
10 the sampling timing  $t_1$ , the ratio  $R_h$  and an offset  
component stored at a nearest position  $x$  after the  
sampling timing  $t_1$  may be used.

Incident energies are obtained at sampling timings  
 $t_2$  to  $t_5$  in the same manner as described above. In this  
15 case, the incident energy  $E_a$  is obtained at the  
sampling timings  $t_1$  and  $t_3$ ; the incident energy  $E_b$  is  
obtained at the sampling timings  $t_2$  and  $t_5$ ; and the  
incident energy  $E_c$  is calculated at the sampling timing  
20  $t_4$ .

Note that an incident energy may be obtained by  
using the average value of data obtained at sampling  
time intervals  $\Delta t$  (e.g., in the time interval between  
the sampling timings  $t_1$  and  $t_2$ ), similar to the first  
embodiment. Assume that the digital sampling interval  
25 for the ratios  $R_h$  and offset components is set to be 25  
 $\mu m$  on a reticle; the sampling time interval  $\Delta t$  between  
the sampling timings  $t_1$  and  $t_2$  is set to be 5 msec; and

1 a scan speed  $V$  is set to be 50 mm/sec. In this case,  
10 ratios  $R_h$  and 10 offset components are obtained as  
sampled data in the sampling time interval  $\Delta t$  between  
the sampling timings  $t_1$  and  $t_2$ . Hence, similar to the  
5 first embodiment, the incident energy  $E_b$  may be  
obtained on the basis of data obtained by averaging the  
10 ratios  $R_h$  and the 10 offset components,  
respectively.

When the incident energy is obtained, a variation  
10 in magnification at each sampling timing is obtained  
from  $\Delta M/E$ , and the reduction rate of magnification in  
each sampling time interval is obtained from the time  
constant  $T$  in the same manner as in the first  
embodiment. As a result, an envelope connecting the  
15 values at the respective sampling timings is set as a  
magnification variation characteristic, thus obtaining  
the magnification variation characteristic shown in  
shown in Fig. 8B. An imaging characteristic controller  
30 determines the control amount of a pressure control  
20 system 40 and the driving amounts of driving elements  
31, 34, and 35 so as to change the magnification in  
accordance with the magnification variation  
characteristic shown in Fig. 8B, thereby correcting the  
magnification.

25 In this embodiment, the ratios  $R_h$  and offset  
components are loaded by moving the reticle stage RST  
in one direction. For this reason, when the reticle

1 stage RST is to be scanned in a direction different  
from the loading direction of the ratios Rh and the  
offset components, these data must be read out in the  
opposite direction.

5 In the first and second embodiments, information  
about the transmittance of a reticle and information  
about light reflected by a wafer are stored in  
accordance with the coordinate position of the reticle.  
However, since the wafer stage WST is scanned at the  
10 same time, the same effect as that described above can  
be obtained even if these pieces of information are  
stored with reference to the coordinate position of the  
wafer stage or time. When storage of data is to be  
performed with reference to the coordinate position, an  
15 interferometer counter must be reset to "0" at the  
start of a scan operation, or the coordinate position  
at the start of a scan operation must be stored. When  
storage of data is to be performed with reference to  
time, the time base scale needs to be changed because  
20 the scan speed changes with a change in exposure time  
owing to the sensitivity of a resist. Note that  
although the precision slightly deteriorates, in the  
above embodiments, the variation characteristic of  
imaging characteristic of the projection optical system  
25 PL may be obtained on the basis of only the amount of  
light which is incident on the projection optical  
system PL through a reticle.

1           When the illumination condition is changed upon  
replacement of an aperture stop 29, the passing  
position of a light beam in the projection optical  
system PL changes, and hence the variation  
5   characteristic of imaging characteristic changes. For  
example, a thermal time constant and the like  
associated with a variation in magnification change.  
Therefore, information (e.g., a thermal time constant)  
about the variation characteristic of imaging  
10   characteristic must be replaced every time the  
illumination condition is changed upon replacement of  
the aperture stop 29.

Fig. 9 shows the positional relationship between  
the reticle blind 8 viewed from above, a projection  
15   field if, and a pattern area PA of the reticle R. In  
this case, the reticle blind 8 is constituted by two  
light-shielding plates 8A and 8B. The light-shielding  
plate 8B has a U shape when viewed from above. The  
light-shielding plate 8B has a straight edge  $EGx_2$   
20   defining an illumination area in the scan direction (x  
direction), and straight edges  $EGy_1$  and  $EGy_2$  defining  
the illumination area in the y direction perpendicular  
to the scan direction. The light-shielding plate 8A  
has a straight edge  $EGx_1$  parallel to the edge  $EGx_2$  of  
25   the light-shielding plate 8B to define the illumination  
area in the scan direction. The light-shielding plate  
8A is designed to be movable in the x direction with

1 respect to the light-shielding plate 8B. With this  
structure, the width of the slit-like illumination area  
IA can be changed in the scan direction. The  
light-shielding plate 8B may also be designed to be  
5 translated in the x direction such that the edges  $EGx_1$   
and  $EGx_2$  defining the illumination area in the scan  
direction are set to be symmetrical with respect to an  
optical axis IX. Fig. 10 is a perspective view  
stereoscopically showing the intensity distribution of  
10 illumination light which is incident on the reticle R  
through the reticle blind 8 shown in Fig. 9. Referring  
to Fig. 10, a direction along the optical axis IX is  
defined as an intensity axis I. No significant problem  
is posed when a continuous light source such as a  
15 mercury discharge lamp is used as an illumination light  
source. However, when a pulse light source is to be  
used, if the illuminance distribution in the scan  
direction exhibits a normal rectangular shape, exposure  
light amount irregularity tends to occur in one shot  
20 area on the wafer W because of variations in  
superposition amount or in the number of times of  
superposition at two end portions of the illuminance  
distribution in the scan direction.

For this reason, as shown in Fig. 10, at least end  
25 portions of the illuminance distribution in the scan  
direction are caused to have almost uniform  
inclinations (width  $\Delta Xs$ ). Referring to Fig. 10, a

1 length YSp of the illuminance distribution in the y  
direction is set to cover the length of the pattern  
area PA of the reticle R in the y direction, and a  
length (slight width) XSp of the illuminance  
5 distribution in the x direction is optimally determined  
in consideration of a target exposure light amount for  
the photoresist on the wafer W, the scan speeds of the  
reticle stage RST and the wafer stage WST, the pulse  
oscillation frequency of a pulse light source (if it is  
10 used), the intensity of illumination light, and the  
like. As shown in Fig. 10, in order to incline the two  
ends of the illuminance distribution by the width  $\Delta x_s$ ,  
the edge EGx<sub>1</sub> of the light-shielding plate 8A and the  
edge EGx<sub>2</sub> of the light-shielding plate 8B in Fig. 9 may  
15 be shifted from a position conjugate to the pattern  
surface of the reticle R in a direction along the  
optical axis IX by a predetermined amount so as to  
project slightly defocused images of the edges EGx<sub>1</sub> and  
the EGx<sub>2</sub> onto the reticle R. When, however, sharp  
20 images of the edges EGY<sub>1</sub> and EGY<sub>2</sub> in a non-scan  
direction are to be formed on the pattern surface of  
the reticle R, the edges EGY<sub>1</sub> and EGY<sub>2</sub> must be  
accurately located at a position conjugate to the  
pattern surface of the reticle R. For this reason, the  
25 edges EGY<sub>1</sub> and EGY<sub>2</sub> are accurately located within a  
conjugate plane, and the edges EGx<sub>1</sub> and EGx<sub>2</sub> are located  
within a plane slightly shifted from the plane position

1 of the edges  $EGy_1$  and  $EGy_2$  to the light source side. In  
addition, in order to variably change the longitudinal  
dimension (length  $YSp$ ) of the slit-like illumination  
area  $IA$ , the edges  $EGy_1$  and  $EGy_2$  must also be designed  
5 to be movable in the  $y$  direction. If the illuminance  
distribution shown in Fig. 10 is uniformly inclined in  
the  $y$  direction, as indicated by an imaginary line  $LLi$ ,  
the exposure light amount at a portion of a shot area  
which is exposed at a position  $ya_1$  in the  $y$  direction  
10 differs from that at a portion of the shot area which  
is exposed at a position  $ya_2$ . For this reason, it is  
preferable that an intensity  $I(ya_1)$  at the position  $ya_1$   
and an intensity  $I(ya_2)$  at the position  $ya_2$  be measured  
to finely adjust the slit width  $XSp$  in the  $y$  direction  
15 in accordance with a ratio  $I(ya_1)/I(ya_2)$ . Let  $XSp(ya_1)$   
be the width of the slit-like illumination area  $IA$  in  
the scan direction at the position  $ya_1$  in the  $y$   
direction, and  $XSp(ya_2)$  be the width in the scan  
direction at the position  $ya_2$ . In this case, the edges  
20  $EGx_1$  and  $EGx_2$  are inclined (rotated) relative to each  
other from the parallel state within the  $x$ - $y$  plane so  
that  $I(ya_1)/I(ya_2) = XSp(ya_2)/XSp(ya_1)$  is established.  
That is, the slit-like blind opening shown in Fig. 9 is  
25 formed into a slightly trapezoidal shape. With this  
arrangement, an accurate amount of exposure light can  
be given to each point in a shot area even with slight

1 illuminance irregularity (uniform inclination) of  
slit-like illumination light in a non-scan direction.

When a pulse light source is to be used, pulse  
emission must be performed with a specific positional  
5 relationship while the reticle R and the wafer W are  
relatively scanned. Fig. 11 illustrates illuminance  
characteristics in the scan direction when pulse  
emission is performed with the specific positional  
relationship. In pulse emission, since the peak  
10 intensity value of each pulse varies, pulse emission  
(trigger operation) is performed at intervals of a  
distance into which the width ( $XP_s + \Delta X_s$ ) of the  
slit-like illumination area IA in the scan direction  
can be divided by a predetermined integer value  $N_p$   
15 (excluding 1) when the illumination area IA is defined  
by an intensity  $I_m/2$  where  $I_m$  is the average value of  
the intensities of pulse light. Assume that the width  
( $XP_s + \Delta X_s$ ) of the slit-like illumination area IA on  
the reticle is 8 mm, and the integer value  $N_p$  is 20.  
20 In this case, the pulse light source may be caused to  
emit pulse light every time the reticle R is  
scanned/moved by 0.4 mm. The integer value  $N_p$  is the  
number of pulses superposed at an arbitrary point on  
the wafer W. Therefore, in order to achieve a desired  
25 exposure precision on a wafer by averaging variations  
in peak intensity value of each pulse, the minimum  
value of the integer value  $N_p$  is automatically

1 determined in accordance with the variations in  
intensity of each pulse. The minimum value of the  
integer value  $N_p$  is expected to be about 20 from the  
performance of an existing pulse light source (e.g., an  
5 excimer laser).

Referring to Fig. 11, since the integer value  $N_P$   
is set to be 5, the inclination of the trailing end  
portion of the illuminance distribution of the first  
pulse in the scan direction overlaps the inclination of  
10 the leading end portion of the illumination  
distribution of the sixth pulse in the scan direction.  
In addition, at the start or end of a scan/exposure  
operation, pulse oscillation is started from a state  
wherein the entire slit-like illumination area IA  
15 (width:  $X_Ps + 2\Delta Xs$ ) is located outside the pattern area  
PA of the reticle R, and the pulse oscillation is  
stopped when the entire illumination area IA (width:  
 $X_Ps + 2\Delta Xs$ ) reaches the outside of the pattern area PA.

Two methods of triggering a pulse light source can  
20 be considered. One method is a position  
synchronization trigger method of supplying a trigger  
signal to the pulse light source for a predetermined  
moving amount in response to a measurement value  
obtained by the laser interferometer 14 (or 19) for  
25 measuring the position of the reticle stage RST (or the  
wafer stage WST) in the scan direction. The other  
method is a time synchronization trigger method of

1 generating clock signals at predetermined time  
intervals (e.g., 2 msec) based on the constant speeds  
of the reticle stage RST and the wafer stage WST,  
assuming that constant speed control therefor is  
5 reliable, and supplying the signals, as trigger  
signals, to the pulse light source. The two methods  
have their own merits and demerits and hence may be  
selectively used. In the time synchronization trigger  
method, however, the generation start timing and stop  
10 timing of clock signals must be determined in response  
to measurement values obtained by the laser  
interferometer 14 or 19.

If the highest priority is given to the  
minimization of the exposure processing time for one  
15 shot area, the speeds of the reticle stage RST and the  
wafer stage WST, the width (XPs) of the slit-like  
illumination area IA, and the peak intensity of pulses  
are preferably set so that the pulse light source  
oscillates at about the rated maximum oscillation  
20 frequency (a predetermined maximum frequency), provided that a  
target exposure amount can be obtained.

Furthermore, as described in each embodiment, when  
various data are to be formed by sampling the outputs  
Sa and Sb from the photoelectric sensor 28 and the  
25 reflected light sensor 27 while scanning only the  
reticle R, or when the pulse light source is oscillated  
by the time synchronization trigger method, the outputs

- 1 Sa and Sb during a scan/exposure operation may be sampled in response to trigger clock signals.

5

10

15

20

25